

Forward jets in hadron-hadron collisions

F. Hautmann

Department of Theoretical Physics, University of Oxford, Oxford OX1 3NP

Abstract

This talk discusses basic aspects of forward production of jets in pp collisions at high energy, including i) issues on QCD factorization for hard processes at large rapidities, and ii) the role of forward jet measurements at the LHC to investigate contributions to parton showers from large-angle gluon radiation and from multiple parton interactions.

1. Introduction

Physics in the forward region at hadron colliders is traditionally dominated by soft particle production. With the start of the LHC, forward physics turns into a largely new field [1–3] because, due to the phase space opening up at large center-of-mass energies, both soft and hard production processes become relevant and, thanks to the unprecedented reach in rapidity of the experimental instrumentation, it becomes possible to carry out a program of jet physics in the forward region. Hard processes at forward rapidities enter the LHC physics program in an essential way both for QCD studies and for new particle searches, e.g. in vector boson fusion search channels for the Higgs boson [4, 5].

Forward production of high p_T brings jet physics into a region characterized by multiple energy scales and asymmetric parton kinematics. It has long been recognized that reliable theory predictions in this region require the resummation of high-energy QCD corrections [6, 7]. For the LHC forward jet kinematics, QCD logarithmic corrections in the large rapidity interval (of high-energy type) and in the hard transverse momentum (of collinear type) may both be quantitatively significant [2]. The theoretical framework to resum consistently both kinds of logarithmic corrections to all perturbative orders is based on QCD high-energy factorization at fixed transverse momentum [8]. This factorization program is carried through in [9] for forward jet hadroproduction. We discuss this briefly in Sec. 2.

Besides these different types of radiative corrections to single parton scattering, the need for realistic Monte Carlo simulations of forward particle production also raises the question of whether non-negligible effects may come from multiple parton interactions [10]. Such

multiple interactions are modeled in parton-shower event generators used to simulate final states at the LHC [11–14], and form the subject of a number of current efforts [15–22] to construct approaches that incorporate multiple parton scatterings.

The capabilities of forward + central detectors at the LHC suggest the possibility to make a combined phenomenological study of multi-parton interactions versus higher-order radiative contributions to single-parton interaction by examining correlations of one forward and one central jet [23] in rapidity and azimuth (Fig. 1). We show results on this in Sec. 3.

Because forward jet production probes the gluon density function for small x , it can naturally be used to investigate possible nonlinear effects [24] at high parton density. The formulation [9] at fixed transverse momentum is well-suited for describing the approach to the high-density region, as it is designed to take into account both the effects from BFKL evolution associated with the increase in rapidity and also the effects from increasing p_T described by renormalization group, which are found to be also quantitatively significant [25] for studies of parton saturation. See e.g. [26] for first Monte Carlo calculations along these lines, and [27] for extension to nucleus-nucleus collisions.

Many of the theoretical issues that underlie forward jet physics, from perturbative QCD resummations to approaching the saturation region to parton-showering methods beyond leading order, depend on the notion of transverse momentum dependent, or unintegrated, parton distribution functions (u-pdfs). (See [28] for recent reviews on this topic.) In the calculations presented below we take the high-energy definition of u-pdfs [8], namely, we rely on the fact that for small x u-pdfs can be defined gauge-invariantly (and can be related to the

ordinary pdfs renormalized in the minimal subtraction scheme $\overline{\text{MS}}$ [29]) by going to the high-energy pole in physical amplitudes [8]. More general characterizations, valid over the whole phase space, are desirable, and currently the subject of much activity. Recent results in this area, see e.g. [30–36], are likely to eventually have a bearing on forward jet physics.

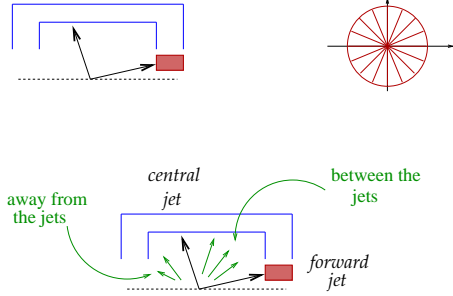


Figure 1: (top) Jets in the forward and central detectors, and azimuthal plane segmentation; (bottom) particle and energy flow in the inter-jet and outside regions.

In the next section we discuss the high-energy factorized form of the forward jet cross section. In Sec. 3 we discuss applications to forward-central jet correlations. We give conclusions in Sec. 4.

2. Forward jet hadroproduction cross sections

The presence of multiple large-momentum scales in the LHC forward jet kinematics brings up the issue [2, 3, 37, 38] of whether fixed-order next-to-leading calculations reliably describe the production process or significant contributions arise beyond fixed order which call for perturbative QCD resummations. If realistic phenomenology of hadronic jet final states requires taking into account at higher order both logarithmic corrections in the large rapidity interval (of BFKL type) and logarithmic corrections in the hard transverse momentum (of collinear type), QCD factorization at fixed transverse momentum can be used to achieve this [9].

The k_T -factorized form of the forward jet hadroproduction cross section is represented in Fig. 2. Initial-state parton configurations contributing to forward jets are asymmetric, with the parton in the top subgraph being probed near the mass shell and large x , while the parton in the bottom subgraph is off-shell and small- x . The jet cross section differential in the final-state transverse momentum Q_t and azimuthal angle φ is given schemat-

ically by

$$\frac{d\sigma}{dQ_t^2 d\varphi} = \sum_a \int \phi_{a/A} \otimes \frac{d\hat{\sigma}}{dQ_t^2 d\varphi} \otimes \phi_{g^*/B}, \quad (1)$$

where \otimes specifies a convolution in both longitudinal and transverse momenta, $\hat{\sigma}$ is the hard scattering cross section, calculable from a suitable off-shell continuation of perturbative matrix elements [9], $\phi_{a/A}$ is the distribution of parton a in hadron A obtained from near-collinear shower evolution, and $\phi_{g^*/B}$ is the gluon unintegrated distribution in hadron B obtained from non-collinear, transverse momentum dependent shower evolution.

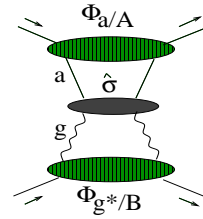


Figure 2: Factorized structure of the cross section.

The multi-parton matrix elements computed in [9] factorize, in the high-energy limit, not only in the collinear emission region but also at finite angle. They can be used to take into account effects of coherence from multi-gluon emission away from small angles, which become important for correlations among jets across long separations in rapidity. We discuss this in the next section.

Note that in the case of forward jet leptonproduction [39] QCD factorization at fixed transverse momentum allows one to compute the high-energy asymptotic coefficients for the coupling of forward jets to deeply inelastic scattering [8, 40]. Since the early phenomenological studies [41], forward jet leptonproduction has been investigated at Hera, and will play a major role at the proposed future lepton facilities [42] (LHeC, EIC). Measurements of forward jet cross sections at Hera [43, 44] have illustrated that neither fixed-order next-to-leading calculations nor standard shower Monte Carlo generators [43, 45], e.g. PYTHIA or HERWIG, are able to describe forward jet ep data. (For related discussions of central jet leptonproduction see [46].) Further analyses of ep data and physics at a future high-energy lepton collider [42] therefore provide additional motivation for developing methods capable of describing jet production beyond the central rapidity region.

The approach above can be combined with parton showering in order to achieve a fully exclusive description of the final states associated to forward production.

To do this, since Eq. (1) involves off-shell matrix elements encoding radiative effects beyond leading order, the basic point is that one needs a scheme for merging consistently the hard radiation from the short distance matrix element with the radiation from parton showering. In [23] the high-energy factorization is used for this purpose. The other important point for the coupling to parton showers is that because in the forward kinematics one of the longitudinal momentum fractions x in the initial state becomes small (see discussion around Fig. 2), in order to take full account of multi-gluon emission coherence one needs to keep finite- k_T terms in the initial-state parton branching. In the results shown in the next section this is done according to the shower algorithm of [47]. (See [48–50] for recent work on related methods.)

These features of the merging and showering distinguish this approach from calculations in the BFKL picture, see e.g. [51] at the next-to-leading order, in which the parton branching is taken to be collinear. In the picture of Eq. (1) forward jets may be produced either from the hard scatter subprocess or from the parton evolution subprocess. This differs from purely collinear [38] or BFKL [51] approaches in which forward jets are produced by hard matrix elements or impact factors.

3. Forward-central jet correlations at the LHC

At the LHC it is possible to measure events where jet transverse momenta $p_T > 20$ GeV are produced several units of rapidity apart, $\Delta\eta \sim 3 \div 6$ [1, 2]. Such multi-jet states can be relevant to new particle discovery processes as well as new aspects of standard model physics. Ref. [23] investigates correlations between forward and central jets, in the framework discussed in the previous section, examining the effects of finite-angle gluon emission across the large rapidity interval. It compares these with effects of the multi-parton interaction corrections taken into account by [11].

The measurement of the azimuthal correlation of a central and forward jet (Fig. 1) provides a useful probe of how well QCD multiple emissions are described. In [23] it is found that while the average of the azimuthal separation $\Delta\phi$ between the jets is not affected very much as a function of rapidity by finite-angle gluon emissions, the detailed shape of the $\Delta\phi$ distribution is.

The cross section as a function of the azimuthal separation $\Delta\phi$ between central and forward jets reconstructed with the Sicone algorithm [52] ($R = 0.4$) is shown in Fig.3 [23] for different rapidity separations. The solid blue curve is the prediction based on implementing the factorization [9] of Eq. (1) in the parton-

shower event generator [47] (CASCADE); the red and purple curves are the predictions based on calculations with collinear parton-showering [11] (PYTHIA), respectively including multiple interactions and without multiple interactions.

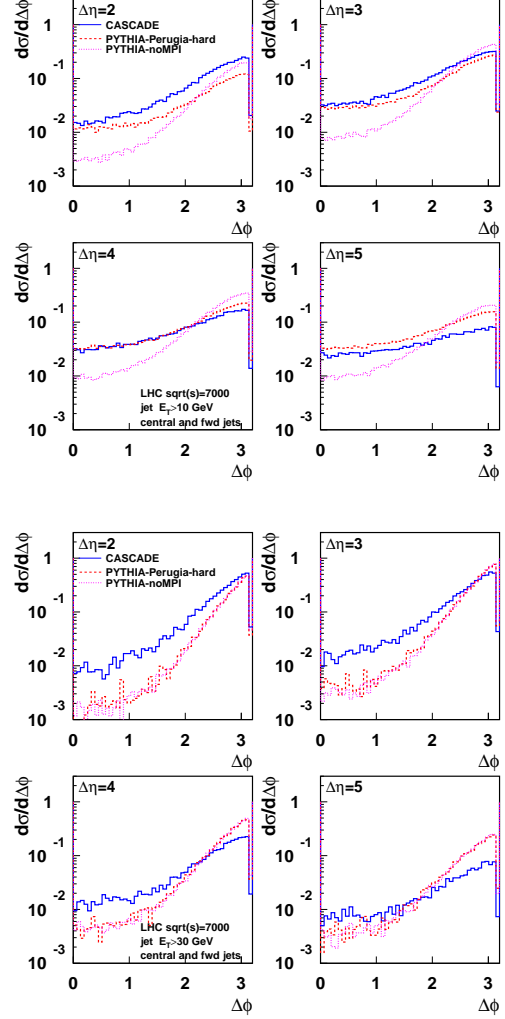


Figure 3: Cross section versus azimuthal separation $\Delta\phi$ between central and forward jet, at different rapidity separations $\Delta\eta$, for jets with transverse energy $E_T > 10$ GeV (top) and $E_T > 30$ GeV (bottom) [23].

The decorrelation as a function of $\Delta\eta$ increases in CASCADE as well as in PYTHIA. In the low E_T region (Fig. 3 (top)) the increase in decorrelation with increasing $\Delta\eta$ is significant. The cross section for jet separation up to $\Delta\eta < 4$ is similar between CASCADE and PYTHIA with multiparton interactions, whereas a clear difference is seen to PYTHIA without multiparton interactions. However, at large $\Delta\eta > 4$ the decorrelation predicted by CASCADE is significantly larger than the prediction from

multiparton interactions. In the higher E_T region (Fig. 3 (bottom)) CASCADE predicts everywhere a larger decorrelation. In this region the influence of multiparton interactions in PYTHIA is small and the difference to CASCADE comes entirely from the different parton shower.

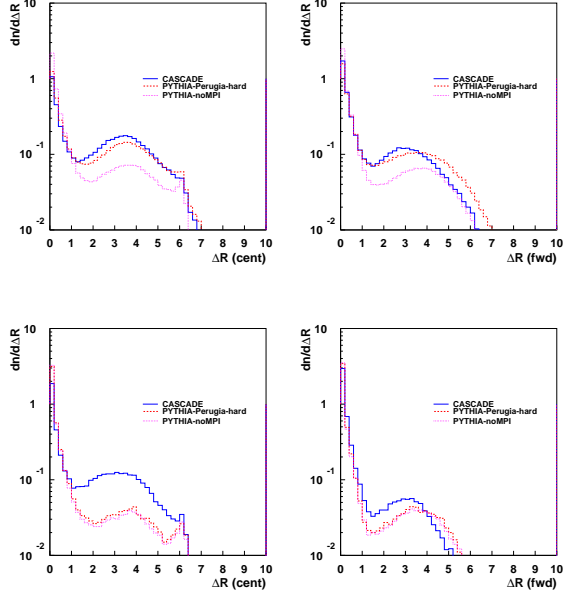


Figure 4: ΔR distribution of the central ($|\eta_c| < 2$, left) and forward jets ($3 < |\eta_f| < 5$, right) for $E_T > 10$ GeV (upper row) and $E_T > 30$ GeV (lower row) [23].

Distinctive effects from the high-energy, noncollinear corrections to parton showers are also observed (Fig. 4 [23]) in the $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ distribution, where $\Delta\phi = \phi_{jet} - \phi_{part}$ ($\Delta\eta = \eta_{jet} - \eta_{part}$) is the azimuthal (rapidity) difference between the jet and the corresponding parton from the matrix element. This distribution probes to what extent jets are dominated by hard partons in the matrix element or receive significant contributions from the showering. The large- ΔR region is seen to be enhanced by noncollinear corrections, and while this signal can be mimicked by multi-parton interactions for low E_T jets, this no longer applies as E_T increases.

4. Conclusion

Jet physics in the forward region at hadron-hadron colliders is a largely new area of experimental and theoretical activity, and enters the LHC program in both new particle discovery processes (see e.g. vector boson fusion channels [4, 5] for Higgs boson searches) and new aspects of standard model physics (e.g., QCD at small x and its interplay with cosmic ray physics, see [3, 53]). In

this kinematic region the evaluation of QCD theoretical predictions is made complex due to the presence of multiple mass scales, and the question arises of whether perturbative QCD resummations and/or corrections from multiple parton interactions are called for in order to go beyond the case of central jets [54, 55].

The factorization [9] allows one to sum consistently to all perturbative orders both large logarithms of rapidity and large logarithms of transverse momentum. Based on this analysis, contributions to the QCD parton cascades from finite-angle multi-gluon emission [23] over wide rapidity intervals are found to affect significantly the predictions for forward jets.

Distinctive effects are seen in particular by considering correlations between forward and central jets [23], e.g. azimuthal correlations. Phenomenological studies based on measurements of these correlations will be relevant for tests of initial state radiation and for the QCD tuning of Monte Carlo event generators. (For the counterpart of this in the case of central jet pairs see the first LHC measurements [54, 55].) They can also be relevant to gain better control on the structure of the final states associated with heavy particle production (e.g., underlying jet activity in scalar boson production [56]).

This analysis can be extended to the case of forward and backward jets. It can thus serve to estimate the size of backgrounds from QCD radiation in Higgs searches from vector boson fusion [4, 5].

Studies of forward high- p_T production, such as those discussed in this article, will be complemented at later stages of the LHC program by studies in other areas of forward physics employing near-beam proton taggers [57]. Both the high- p_T and proton-tagging measurements can contribute to either standard-candle or discovery physics. In addition, both will provide inputs on (hard and soft) forward particle production that will serve for the modeling of high-energy air showers [53] in cosmic ray experiments.

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